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A SURVEY OF THE VARIABILITY IN TISSUE NITROGEN AND PHOSPHORUS CONCENTRATIONS IN MAIZE AND GRAIN SORGHUM

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ABSTRACT

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A literature survey was conducted to determine the variability of tissue N and P concentrations in maize (*Zea mays* L.) and grain sorghum (*Sorghum bicolor* (L.) Moench) shoots, roots, grain, and residues. Tissue N and P concentrations associated with near-optimum yields, the ratio of shoot N to shoot P, the relationship between harvest indexes for N and dry matter, and the relationship between shoot N concentration and grain N concentration were also investigated. For maize at near-optimum yield levels, growth stage has been shown to account for 86% of the variation in shoot N concentration prior to growth stage 8 and 82% of the variation in shoot P concentration prior to growth stage 4. The range of grain sorghum shoot N concentrations was similar to that of maize, but data were inadequate to estimate the range or optimum of grain sorghum P concentrations. The ratio of maize shoot N to shoot P concentration was variable; however, at near-optimum yield levels, the ratio was quite predictable. Maize and grain sorghum root N concentrations were less variable than shoot N concentrations and were not strongly dependent on growth stage. Grain and residue N and P concentrations were variable, but over 70% of the variation in maize grain N concentration was accounted for by shoot N concentration.

INTRODUCTION

In recent years, numerous attempts have been made to simulate soil transformations of N and P and the effects of soil and fertilizer N and P on nutrient uptake by the plant, crop growth, and water pollution. In order to produce reasonable estimates of the effects of crops on soil nutrient transformations, soil erosion, and water quality, simulation models must produce reasonable estimates of crop nutrient content and the distribution of nutrients in the crop. The purpose of this review is to determine: (1) the variability of tissue N and P concentrations of several major fractions of maize (*Zea mays* L.) and grain sorghum (*Sorghum bicolor* (L.) Moench) plants; and (2) the optimum tissue N and P concentrations at different stages of growth. This information can be used to evaluate the estimates of crop nutrient composition produced by crop growth simulation models.

METHODS

Most of the data analyzed in this survey were obtained from studies conducted in North America; however, significant data were also obtained from Asian, European, Australian, and South American studies. Data collected included shoot, root, grain and crop residue N and P concentrations, dry matter harvest index (dry weight of grain/dry weight of shoot), N harvest index (grain N content/shoot N content), and growth stage (Table I) (Hanway, 1963; Vanderlip and Reeves, 1972). Data were obtained from tables, graphs, and histograms. Some inaccuracies were inevitable in the estimation of numerical values from graphical data. This was especially true for the early growth stages when crop dry matter and nutrient content were small in relation to the error associated with the numerical estimate. Sufficient information on crop growth stage (GS) was rarely available; therefore, estimates of GS are also subject to error. However, estimates of GS are probably accurate to ±1 unit, and estimates of dry matter, leaf area, and N and P concentra-

TABLE I

Definitions of growth stages for maize (Hanway, 1963) and grain sorghum (Vanderlip and Reeves, 1972)

Growth stage	Maize	Grain sorghum
0	Emergence. Coleoptile visible at soil surface.	Emergence. Coleoptile visible at at soil surface.
1	Collar of 4th leaf visible.	Collar of 3rd leaf visible.
2	Collar of 8th leaf visible.	Collar of 5th leaf visible.
3	Collar of 12th leaf visible.	Growing point differentiation. Approximately 8 leaf stage.
4	Collar of 16th leaf visible. Tips of many tassels visible.	Final leaf visible in whorl.
5	75% of plants have silks visible.	Boot. Head extended into flag leaf sheath.
6	Kernals in "blister" stage.	Half bloom. Half the plants at some stage of bloom.
7	Very late "roasting ear" stage.	Soft dough.
8	Early dent stage.	Hard dough.
9	Full dent stage.	Physiological maturity. Maximum dry matter accumulation.
10	Physiological maturity.	

tions are probably within 10% of the actual value before GS 5 and within 5% of the actual value after GS 5.

The data were collected from a wide range of genotypes and environments ranging from the field to greenhouse and controlled environment studies. However, except for one study of maize seedling growth (Maizlish et al., Pa. State Univ., personal communication, 1980) only field-grown plants were used to estimate optimum shoot, root, and grain N and P concentrations. With the same single exception, no plants grown in solution culture were used to estimate the range of tissue N concentrations because their concentrations often fell far outside the range of concentrations found in soil-grown plants.

When appropriate, grain weights and N concentrations were converted to a dry matter basis. Similarly, in a few cases, shoot dry matter was calculated from total plant dry matter using Foth's (1962) estimation of the shoot/root ratio at different growth stages.

In this survey, "optimum" and "near-optimum" N and P concentrations refer to tissue nutrient concentrations of plants from treatments in which dry matter at the time of sampling was $\geqslant 0.95$ of the maximum dry matter in the experiment. In a few cases, near-optimum nutrient concentrations were assumed in experiments without N and P fertilizer rate variables because nutrition was reported to be adequate for maximum yields and the concentrations reported were similar to near-optimum concentrations in other experiments.

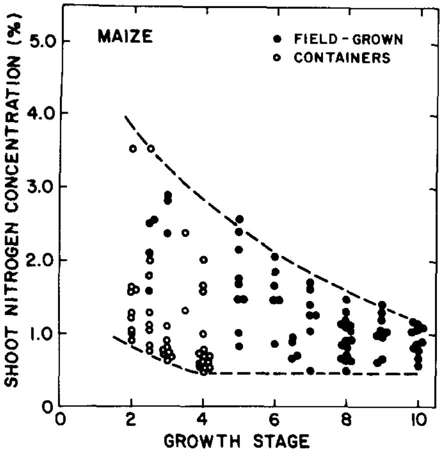
Upper and lower limits of tissue nutrient concentrations were estimated by eye except in cases where the data did not suggest a simple relationship of nutrient concentration with GS. In these cases upper and lower limits were not estimated.

RESULTS AND DISCUSSION

Shoot N and P concentrations

It is well known that in maize and grain sorghum, shoot N and P concentrations decrease with increasing nutrient deficiency and crop age; however, the variability in these concentrations is not well documented. In this survey, maize shoot N concentrations were found to be extremely variable during early growth, especially in pot studies (Fig. 1). For example, at GS 2 (eight collared leaves) maize shoot N concentration ranged from 4% to less than 1%. This variability declined at later growth stages, and at physiological maturity (GS 10) shoot N concentrations prior to GS 5 (silking) in field studies than in pot studies probably reflect the difficulty of obtaining extreme N deficiency in the field. Had the pot studies surveyed been continued past GS 5, shoot N concentrations below the lower limit found in the field (0.45% N) might have been obtained.

When only the near-optimum nitrogen treatments of maize field experiments were considered, growth stage alone accounted for 86% of the varia-



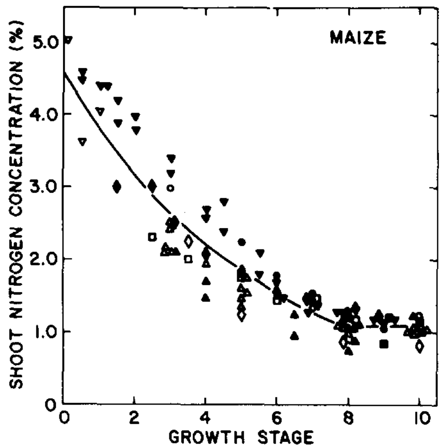


Fig. 1. Relationship between growth stage and maize shoot nitrogen concentration. Field: Robertson et al. (1973); Thom and Watkin (1978); Gonske and Keeney (1969); Hanway (1962a, 1962b); Jordan et al. (1950); Bigeriego et al. (1979); Sayre (1955); Firth et al. (1973); Kafkafi and Bar-Yosef (1971). Containers: Maizlish et al. (1980; personal communication); Terman and Allen (1974a, b); Stewart and Porter (1969). Equation for upper limit: $\ln \hat{Y} = 1.646 - 0.148X$. Equations for lower limit: $X < 4.0$, $\hat{Y} = 1.25 - 0.20X$; $X \geqslant 4.0$, $\hat{Y} = 0.45$.

Fig. 2. Relationship between growth stage and maize shoot nitrogen concentration in field experiments (except Maizlish et al., 1980) from treatments with near-optimum dry matter yields. (●) Robertson et al. (1973); (○) Thom and Watkin (1978); (■) Gonske and Keeney (1969); (□) Hanway (1962a, b); (▲) Jordan et al. (1950); (△) Bigeriego et al. (1979); (◆) Sayre (1955); (◇) Firth et al. (1973); (▼) Kafkafi and Bar-Yosef (1971); (▽) Maizlish et al. (1980; personal communication, 1981). For $X \leqslant 8.0$, $\ln \hat{Y} = 1.52 - 0.181\ X$, $r = -0.93$, $n = 78$. For $X > 8.0$, $\hat{Y} = 1.09$, standard deviation of $\hat{Y} = 0.129$, $n = 17$.

tion in shoot N concentration at or before GS 8 (Fig. 2). The results suggest that, even though maize shoot N concentrations are quite variable among experiments and growth stages, when N nutrition is adequate, growth stage alone is a good predictor of shoot N concentration.

The effect of GS on grain sorghum shoot N concentration was similar to that obtained for maize (Fig. 3). More variation in concentration was found when GS was less than 5 than when it was greater than 5.0. However, both the upper and lower limits of observed N concentrations in grain sorghum were higher than those observed in maize at equivalent growth stages. For example, at physiological maturity shoot N concentrations of grain sorghum ranged from 0.99% to 1.68%; the corresponding range for maize was 0.45% to 1.30%.

It was difficult to determine which grain sorghum shoot N concentrations should be classified as near optimum. In only two studies (D.E. Kissel, Kans. State Univ., personal communication, 1981; Shipley et al., 1971) did either fertilizer N or soil NO_3 — N reserves greatly exceed plant uptake. The highest fertilizer N rate reported by Kissel (personal communication, 1981) was 336

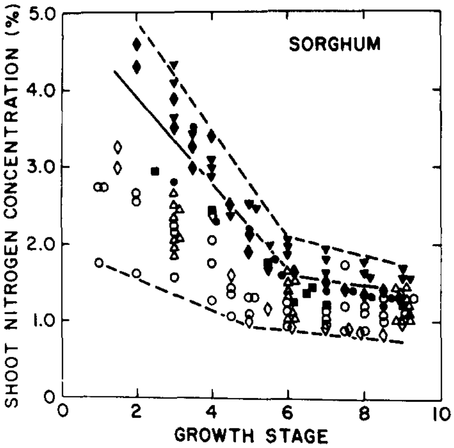


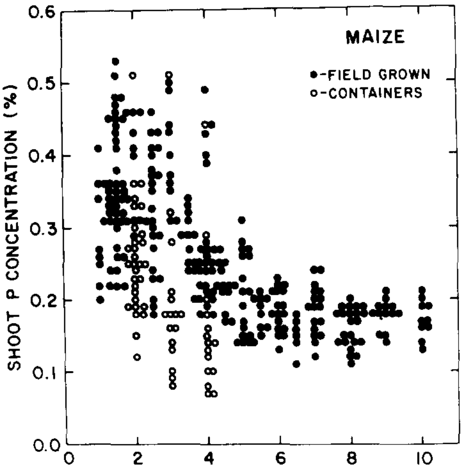
Fig. 3. Sorghum shoot nitrogen concentrations at different growth stages. Solid symbols, near-optimum N levels; open symbols, sub-optimal N levels; (○) Roy and Wright (1973, 1974); (●) Eck and Musick (1979a, b); (■) Shipley et al. (1971); (△) Turkhede and Prasad (1978); ( ) Hay (1975); (♦, ◇) D.E. Kissel (personal communication, 1981). Equations for upper limit: $X \leqslant 6.0$, $\hat{Y} = 6.3 - 0.70X$; $X > 6$, $\hat{Y} = 2.8 - 0.12X$. Equations for lower limit: $X \leqslant 5.0$, $\hat{Y} = 2.0 - 0.22X$; $X > 5.0$, $\hat{Y} = 1.2 - 0.05X$. Equations for near-optimum concentrations: $X \leqslant 6.0$, $\hat{Y} = 5.05 - 0.516X$, $r = -0.85$, $n = 34$. For $X \geqslant 6.0$, $\hat{Y} = 2.12 - 0.081X$, $r = -0.38$, $n = 29$.

kg N/ha, and Shipley et al. (1971) reported 578 kg NO_3—N to 122 cm. In one study (Turkhede and Prasad, 1978), the highest fertilizer N rate (150 kg N/ha) slightly exceeded crop N uptake (120 to 140 kg N/ha). In two studies (Roy and Wright, 1973, 1974; Hay, 1975), crop N uptake exceeded the amount of N applied (112 to 120 kg N/ha). None of the studies included enough rates of fertilizer N to obtain a detailed N response curve; therefore, the four treatments with the highest shoot N concentrations throughout the growth of the crop (Shipley et al., 1971; Kissel, personal communication, 1981; Hay, 1975; Eck and Musick, 1979a, b) were selected to represent near-optimum shoot N concentrations.

Since few fertilizer N rates were used in most studies shown in Fig. 3, detailed yield response curves are not available. As a result, we cannot be certain that the highest shoot N concentrations shown in Fig. 3 do not represent luxury consumption of N. Likewise, we cannot be certain that some of the lower shoot N concentrations are not near optimum. For example, grain yield and grain N concentration data suggest that the highest shoot N concentrations reported by Turkhede and Prasad (1978) are near optimum levels, even though tissue N concentrations are lower than in other studies at GS 3 and 6. If the above were the case, near-optimum shoot N concentrations would be slightly lower than those shown in Fig. 3. More detailed fertilizer N response data are needed to verify the near-optimum concentrations proposed in Fig. 3.

The variation in maize shoot P concentration observed in this study is shown in Fig. 4. Like N concentrations, shoot P concentrations are more variable in young plants than in older plants, and data from pot studies are more variable than those from field studies. Because of this variation, it was not possible to draw smooth upper and lower limits of maize shoot P concentrations. When near-optimum P concentrations were selected from the data in Fig. 4, two trends were observed (Fig. 5). From growth stages 1.5 through 4.0, optimum shoot P concentrations decreased rapidly with increasing growth stage. During this period, growth stage accounted for over 95% of the variation in optimum shoot P concentration. After growth stage 4 (tassel peeping), the shoot P concentration associated with near-optimum yield decreased more slowly as growth stage increased. Since only four studies were used to determine near-optimum shoot P concentrations, more data are needed to confirm the relationship shown in Fig. 5.

Only one study was found in which shoot P concentrations were monitored throughout a grain sorghum crop and in which fertilizer P was a treatment variable (Roy and Wright, 1973, 1974). The highest yielding treatment in that study had shoot P concentrations similar to those shown in Fig. 5 for maize. At and after GS 5 (boot, head extended into flag leaf sheath)



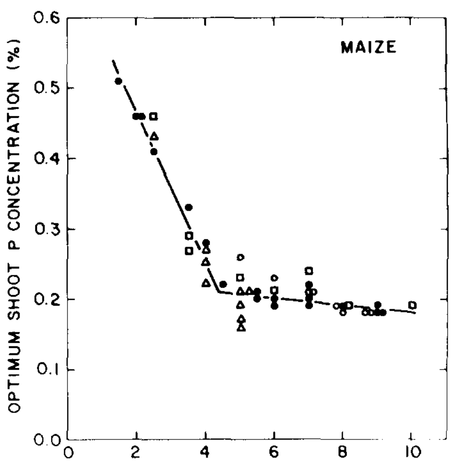


Fig. 4. Relationship between growth stage and maize shoot P concentration from the following studies: Kafkafi and Bar-Yosef (1971); Robertson et al. (1973); Jordan et al. (1950); Hanway (1962a, b); Nielsen and Barber (1978); Belcher and Ragland (1972); Baker et al. (1970); Schenk and Barber (1979a, b); Terman and Allen (1974a, b).

Fig. 5. Relationship between growth stage and maize shoot P concentration in treatments of field experiments with near-optimum dry matter yields. (•) Kafkafi and Bar-Yosef (1971); (○) Robertson et al. (1973); (□) Hanway (1962a, b); (▽) Belcher and Ragland (1972). When growth stage $\leqslant$ 4.0: $\hat{Y} = 0.684 - 0.108X$, $r = -0.907$, $n = 13$. When growth stage > 4.0: $\hat{Y} = 0.238 - 0.0056X$, $r = -0.409$, $n = 30$.

shoot P concentration was 0.2% ± 0.06%. This suggests that the optimum shoot P concentration of grain sorghum is similar to that of maize after GS 5, but more data are needed to confirm the relationship.

Shoot N/P ratios

When fertilizer N is applied, uptake of P is often stimulated, especially when the N and P are applied in a band. The increase in P uptake is often greater than the corresponding increase in dry matter due to N fertilization, and higher tissue concentrations of both N and P result (Viets et al., 1954; Bennett et al., 1962; Cole et al., 1963). In addition, maize earleaf concentrations of N and P are often highly correlated in factorial N × P fertilizer rate experiments, and earleaf N/P ratios are quite stable in high-yielding treatments of these experiments (Escano et al., 1981a, b). Maize shoot N/P ratios are quite variable among and within experiments reviewed in this survey (Fig. 6); however, shoot N/P ratios were much more predictable at near-optimum N and P fertility, especially after GS 6 ("blister" stage) (Fig. 7). More data are needed to confirm the relationship shown in Fig. 7.

Insufficient data were obtained to estimate the variability of shoot N/P ratios in grain sorghum.

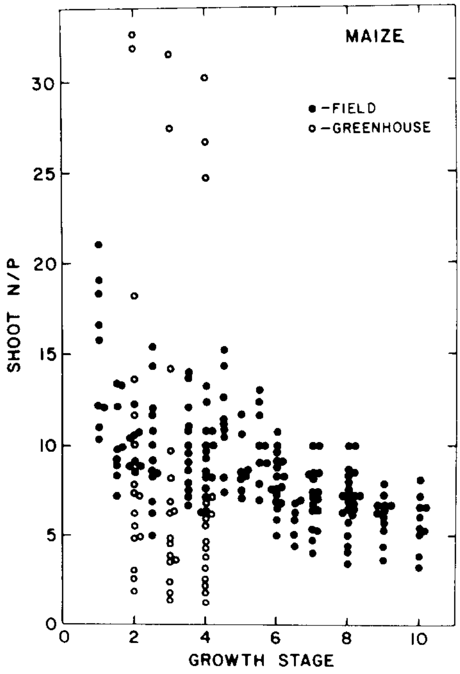


Fig. 6. Relationship between growth stage and maize shoot N : P ratio from the following studies. Field: Kafkafi and Bar-Yosef (1971); Belcher and Ragland (1972); Hanway (1962a, b); Jordan et al. (1950); Robertson et al. (1973). Greenhouse: Terman and Allen (1974a, b).

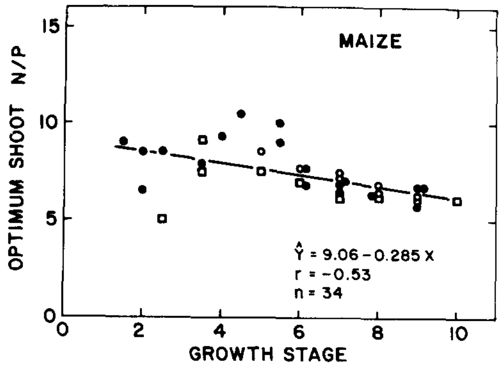


Fig. 7. Relationship between growth stage and maize shoot N : P ratio in treatments of field experiments with near-optimum dry matter yields. (•) Kafkafi and Bar-Yosef (1971); (○) Robertson et al. (1973); (□) Hanway (1962a, b).

Root N and P concentrations

Few data are available on the variation in root N and P concentrations in maize and grain sorghum, especially from field studies. However, the data available suggest that growth stage has little effect on root N concentrations (Figs. 8 and 9). The only field study encountered in which root P concentrations were measured as a function of GS was that of Myers (1980). The results suggest that root P concentrations are not affected by GS. The mean root P concentration in this study was 0.041% with a standard deviation of 0.0047%. However, the concentrations reported by Myers (1980) are lower than those reported from pot studies with maize (Schenk and Barber, 1979a, b) where root P concentrations ranged from 0.10% to 0.25% depending on levels of plant-available soil P.

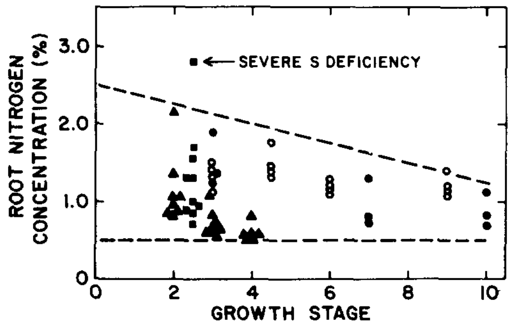


Fig. 8. Apparent limits of maize and grain sorghum root N concentrations. Sorghum: (○) Myers (1980). Maize: (•) Thom and Watkin (1978); (▪) Stewart and Porter (1969); (▲) Terman and Allen(1974). Equation for upper limit: $\hat{Y}$ = 2.5 – 0.125X. Equation for lower limit: $\hat{Y}$ = 0.50.

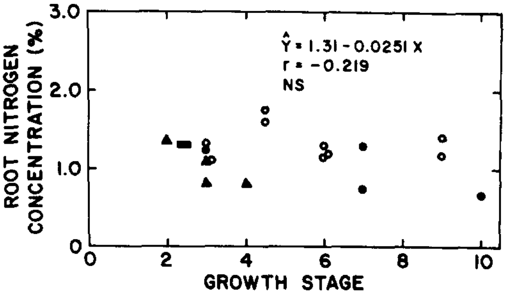


Fig. 9. Maize and sorghum root nitrogen concentrations at different growth stages with near-optimum nitrogen levels for shoot dry matter production. Means: for maize, $\hat{Y}$ = 1.06, standard deviation = 0.28; for sorghum, $\hat{Y}$ = 1.33, standard deviation = 0.21. Symbols as in Fig. 8.

Grain N concentrations

Crop growth simulation models which depend on soil N balances to predict N availability to the crop require realistic estimates of N removed in the grain. Grain N concentrations obtained in this survey varied by more than two-fold in maize and by more than three-fold in grain sorghum (Table II).

TABLE II

Mean optimum, standard deviation of the mean optimum, and range of grain N concentrations (% of dry matter) in maize and grain sorghum (numbers in parentheses are the numbers of treatments used to establish each value)

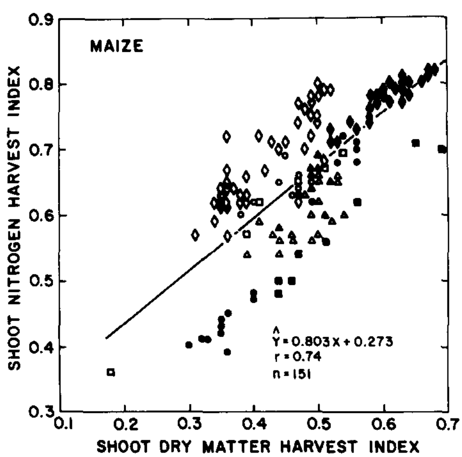
	Optimum		Range
	Mean	Standard deviation	
Maize	1.58 (82)	0.17	0.90—2.09 (261)
Grain sorghum	1.67 (53)	0.25	1.02—3.20 (282)

Sources: Maize: Bigeriego et al. (1979), Boswell (1977), El-Hattab et al. (1980), Hanway (1962b), Jordan et al. (1950), Kurtz et al. (1952), Lang et al. (1956), D.J. Lathwell (personal communication), Liegel and Walsh (1976), Ohlrogge et al. (1943), Perry and Olson (1975), Russelle et al. (1981), Stevenson and Baldwin (1969). Grain sorghum: Asher and Cowie (1974), Brawand and Hossner (1976), Burleson et al. (1957), Herron et al. (1963), Miller et al. (1964), Mirhadi and Kobayashi (1981), Nelson (1952), Patel et al. (1975), Perry and Olson (1975), Roy and Wright (1973), Stone and Tucker (1969), Turkhede and Prasad (1978), Welch et al. (1966), Worker and Ruckman (1968).

The mean near-optimum grain N concentration of grain sorghum was slightly greater than that of maize (Table II). The variability of near-optimum grain N concentrations was quite large. The range of N concentrations within two standard deviations of the near-optimum mean was 1.28% to 1.92% for maize and 1.22% to 2.06% for grain sorghum.

The mean near-optimum grain N concentration of 1.58% is near the mean near-optimum grain N concentration of 1.52% to 1.54% found by Pierre et al. (1977a, b) in 13 site-years of N-rate experiments in Iowa. However, the standard deviation of the mean was 0.17% (n = 82) in this survey compared with 0.08% (n = 20) in Pierre et al. (1977a). In contrast to the results of Pierre et al. (1977a), no significant relation could be found between grain N concentration and relative grain yield. The greater variability found in this study may result from the use of data from a wider range of environmental conditions and maize germplasm (Russell and Pierre, 1980) than were obtained in the 13 site-years of data in Iowa.

Because of the wide variation in grain N concentrations, two other approaches were used to estimate N removed in the grain. Under some circumstances, it might be useful to estimate the percentage of total shoot N in the grain at harvest. Grove et al. (1980) showed that in maize the harvest index for N varies among seasons and soil N fertility levels. In this survey the harvest index for dry matter accounts for 55% and 29% of the variability in N harvest index in maize and grain sorghum, respectively (Figs. 10 and 11). Though a positive relationship was found between harvest indexes for shoot dry matter and shoot nitrogen, variation in this relationship exists among studies. This variability is probably due to both the effects of weather on plant N uptake



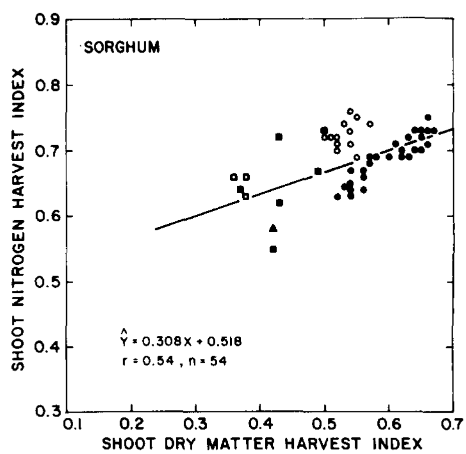


Fig. 10. Relationship between maize shoot dry matter harvest index and shoot nitrogen harvest index. (●) Lathwell (personal communication 1969 and 1970 crops, r = 0.98, n = 20; (○) Lathwell, 1981 crop, r = 0.61, n = 10; (■) Lathwell, 1972 crop, r = 0.97, n = 10; (□) Jordan et al. (1950), r = 0.99, n = 6; (▲) Russelle et al. (1981), r = 0.60, n = 8; (△) Ohlrogge et al. (1943), r = 0.92, n = 20; (◆) Perry and Olson (1975), r = 0.92, n = 32; (◇) Grove et al. (1980), r = 0.89, n = 45.

Fig. 11. Relationship between grain sorghum shoot dry matter harvest index and shoot harvest index. (●) Perry and Olson (1975); (○) Herron et al. (1963); (■) Roy and Wright (1973, 1974); (□) Burleson et al. (1957); (▲) Shipley et al. (1971).

and grain dry matter accumulation, and the effects of genotype on redistribution of N to the grain (Beauchamp and Estes, 1976; Mite, 1980).

Perhaps a more useful relationship is that between shoot N concentration and grain N concentrations in maize (Fig. 12), which can be used to evaluate estimates of grain N concentration produced by crop growth simulation models that simulate the movement of dry matter and N to the grain. Insufficient data were available to evaluate the same relationship in grain sorghum.

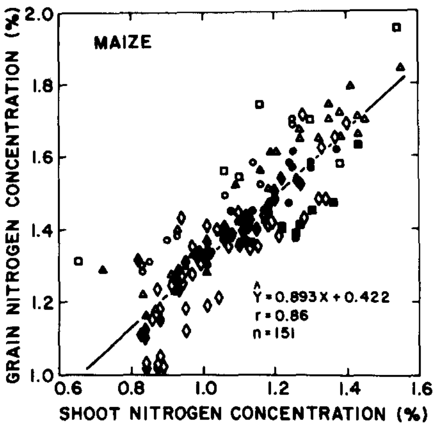


Fig. 12. Relationship between maize shoot N concentration and grain N concentration. Sources: (●) Lathwell (Cornell Univ., NY, personal communication, 1981), 1969 and 1970 crops; (○) Lathwell, 1971 crop; (■) Lathwell, 1972 crop; (□) Jordan et al. (1950); (▲) Russelle et al. (1981); (△) Ohlrogge et al. (1943); (◆) Perry and Olson (1975); (◇) Grove et al. (1980).

Residue N concentrations

The N concentration of crop residue has a strong influence on immobilization of mineral N when residue is incorporated into the soil. Residue N concentrations obtained in this survey were slightly more variable than grain N concentrations (Table III). For both maize and grain sorghum, residue N concentration varied more than three-fold. As in the case of grain N, the

TABLE III

Mean, standard deviation, and range of stover N concentrations (% of dry matter) for maize and grain sorghum. Numbers of treatments used to establish values in parentheses.

	Mean	Standard deviation	Range
Maize	0.72 (117)	0.21	0.41–1.28
Grain sorghum	0.80 (39)	0.26	0.36–1.26

Sources: Maize: Grove et al. (1980), Lathwell (Cornell Univ., NY, personal communication, 1981), Perry and Olson (1975), Robinson (1973), Russelle et al. (1981). Grain sorghum: Burleson et al. (1957), Herron et al. (1963), Perry and Olson (1975), Turkhede and Prasad (1978).

mean N concentration in grain sorghum residue was slightly higher than that of maize. No near-optimum concentration was calculated because residue N concentration depends on both N uptake and the N demand of the grain. In this context, either high or low residue N concentration could be obtained in high-yielding crops, depending on the balance of N supply and demand.

CONCLUSIONS

This survey provides a data base to which future experimental data can be compared. It also provides an experimental data base for evaluation of the results of crop growth simulation models which are used for yield prediction and which interact with soil nutrient transformation models and water quality models.

The results of the survey indicate the following:

Though shoot N and P concentrations are quite variable, at near-optimum yield levels GS accounts for over 70% of the variation in concentration during the early growth of the plant. As the plant nears maturity the effect of growth stage decreases, but concentration remains relatively stable and predictable.

The ratio of maize shoot N to shoot P concentration is also quite variable; however, at near-optimum yields the ratio is quite predictable, declining from approximately 8.5 at GS 2 to approximately 6.0 at GS 10.

Root N concentrations are less variable than shoot N concentrations and are not strongly dependent on GS.

Grain and residue N and P concentrations are rather variable, even at near-optimum yields; however, over 70% of the variation in grain N concentration can be accounted for by shoot N concentration.

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